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TITLE	AUTHORS	DATES	PAGES
The Place of Solar Thermal Rockets in space	C. C. Selph	May 81	24
Solar Thermal Propulsion from Concept to Reality	Karl J. Iliev	Aug 1996	11
Solar BI-Modal System Concept: Mission Applications, A Preliminary Assessment	Kristi K. Laug, Michael R. Holmes Kurt O. Westerman		5
Dual-Propulsion Technology Reusable Orbit Transfer Vehicle Study	Travis Elkins, Terence Galati		7
Studies of Hafnium-Carbide Wafers using a Thermogravimetric	Domingo G. Castillo, Paul F. Jones		11
One Dimensional Model of a Solar-Thermal Thruster Using a Porous Absorber/Heat Exchanger	Michael R. Holmes	October 15, 1993	29
Evaluation of Hafnium-Carbide Wafers for use in a Solar Calorimeter	Kristi K. Laug, Alan J. Baxter		7
Solar Thermal Propulsion Experiments Design	Kristi K. Laug	1996	11
Porous Disk Test Bed Report of Results	Richard Hurtz	Aug 10, 1990	24
The Solar Propulsion Concept is Alive and Well at the Astronautics Laboratory	Kristi K. Laug	Nov 26, 1993	70
Foam Inflated Rigidized Truss Structure Developed for an SRS Technologies Solar Concentrator	Dean M. Lester, David M. Cannon	1996	8
Fabrication of Thin Film Concentrators for Solar Thermal Propulsion Applications	Paul A. Cierow	1991	7
Scaling Characteristics of Inflatable Paraboloid Concentrators	Mitchell Thomas, Gordon Veal	1991	6
AFRPL Solar-Thermal Rocket Activities	C.C. Selph, G.J. Naujokas	March 1984	9
Dependence of Solar-Thermal Rocket Performance on Concentrator Performance	Michael R. Holmes, Kristi K. Laug	1995	12
A Comparison of the Performance of Seamed and unseamed Inflatable Concentrators	Arthur Palisoc, Mitchell Thomas	1995	10
Society for the Advancement of Material and Process Engineering	Thomas C. Walton, James V. Crivello		10
Ideal Performance of Off-Axis Paraboloid Concentrators for Solar Thermal Propulsion	Michael R. Holmes		7
A Performance Evaluation of an Inflatable Concentrator for Solar Thermal Propulsion	J.P. Paxton, M. R. Holmes		10
Prediction of the Response of a Polyimide Concentrator for Solar Thermal Propulsion	Paul A. Gierow, William R. Clayton, James D. Moore		8
Inflatable Concentrators for Solar Thermal Proulston	William R. Clayton, Paul A. Gierow	1992	6
The Long Term Storability and Expulsion of Rocket Propellants and Oxidizers	Gordon David Elder	Aug 13, 1987	5
Prediction of the Response of a Polyimide Concentrator for Solar Thermal Propulsion	Paul A. Gierow, James D. Moore		11
Conceptual Design Study of a Solar Concentrator	R. Prasinghe, Kristi K. Laug		13
PL (OLAC)/RKAS Concentrator Information	Michael R. Holmes	Feb 11, 1993	29
Dependence of Solar-Thermal Rocket Performance on Concentrator Performance	Michael R. Holmes, Kristi K. Laug	1995	12
Thruster Interface	Michael R. Holmes	May 4, 1994	23
Cumulative Power Plots	Kristi K. Laug		87

SOLAR THERMAL PROPULSION EXPERIMENTS DESIGN

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ABSTRACT

Satellites that are currently under powered or have low photovoltaic (PV) efficiency, may be rejuvenated by dosing them with laser power beamed from earth. Also, current strictly solar thermal propulsion schemes may be able to use laser power as a replacement energy source when they are eclipsed. Several questions must be answered before a multiple use of laser power may be designated. The questions are outlined in the background section of this paper. They deal with gains that may be realized using solar power for operating specific hardware as opposed to laser power. A series of experiments that will give us information we can use to answer the questions will be performed. However, this paper outlines and presents only the design of experiments based upon statistical methods generated by Dr. Genuchi Taguchi.

INTRODUCTION

This paper is focused on the solar thermal experimental matrix and the design thereof that will be used to set up the experiments. Some simple laser power beaming experiments on existing solar thermal propulsion hardware were already performed.¹ Experiments using solar energy as the power source on the very same hardware will soon be performed. The data will be compared to determine differences in performance.

OBJECTIVE

The overall goal is to determine the feasibility of using OL-AC Phillips Laboratory (PL)/RKES's reticulated vitreous carbon calorimeter (RVCC) as a Solar and Laser Powered Rocket Engine (SLPRE). A Solar and Laser Powered Rocket Engine is a propulsion device which consists of a structure with a cavity or surface where either solar or laser energy is focused and captured as thermal energy. This energy is then transferred to a working fluid such as helium or hydrogen. Once the working fluid is heated by the thermal energy it is expanded through a nozzle, producing thrust (kinetic energy).

The testing goal is to collect data for our thruster modeling. Testing this engine will add important data to the

modeled engines database at little cost to OL-AC PL/RKES. Experiments will be performed on the RVCC in the solar furnace at Phillips Lab, Edwards AFB; data collected will be compared with data accumulated during testing in the Chemical Oxygen Iodine Laser (COIL) at Kirtland AFB NM.²

Another goal is to fabricate and fly the solar/laser rocket engine in space. Eventually, one of the SLPREs will undergo exhaustive reliability and maintainability testing at flight conditions in preparation for a space flight test mission from Low Earth Orbit to Geosynchronous Earth Orbit. See the figures below. Fig. 1 is our rendering of a solar powered rocket in space. Fig. 2 is a schematic of the solar powered rocket in Fig. 1.

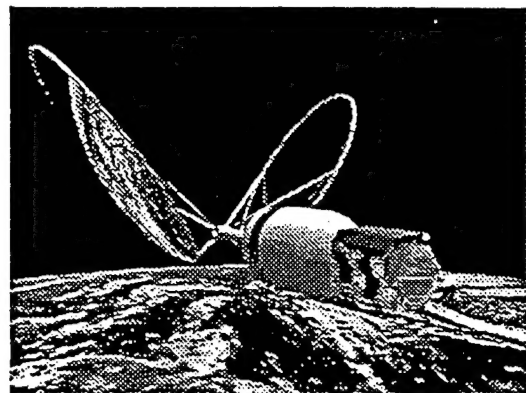


Fig. 1 Solar Powered Rocket

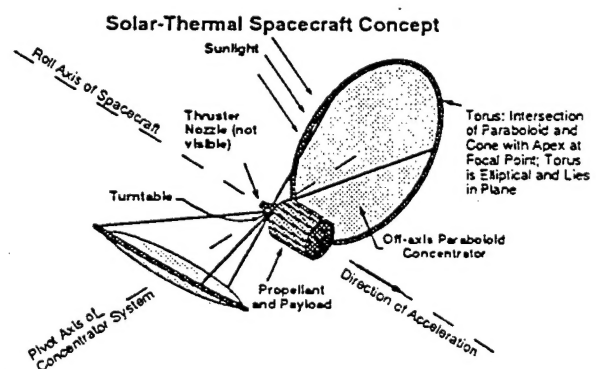


Fig. 2 Solar Thermal Rocket Propulsion Mission Scenario

¹ Kristi K. Laug and John David Holtzclaw, Volumetric Absorber as Solar Engine Utilizing Laser Thermal Power for Energy Input, 1995 Joint Army Navy NASA Air Force (JANNAF) Propulsion Meeting Proceedings, CPIA Publication, Tampa FL, 4-8 December 1995.

² Laug & Holtzclaw, Volumetric Absorber as Solar Engine Utilizing Laser Thermal Power for Energy Input.

The questions which must be answered in order to achieve the goals are: Can current propulsion schemes benefit from using laser and solar power beaming? Can a solar thermal propulsion system use laser power beaming for its primary energy source and visa versa? Sunlight exists in seemingly inexhaustible quantities. Even after laser power beaming is weakened and diffused to the point of inexistence over many thousands of kilometers, sunlight will still be able to be concentrated and focused enough to produce enough heat to propel a solar rocket. It lends itself well for interplanetary missions. Chemical rockets will be slower than solar for interplanetary missions because they thrust once and coast. Solar rockets will still thrust repeatedly, resulting in faster, cheaper trip times for the customer. Can current facilities and personnel be used to experimentally validate the concept? This is the main area Taguchi's Design of Experiments methods can help.³ The method determines the important variables needed to be considered, how all the variables interact with each other, and how to perform the fewest number of experiments while gaining the most knowledge.

BACKGROUND

The Phillips Lab Propulsion Directorate: Participates in the research and development of a wide range of solar, laser, and bi-modal hybrid propulsion systems for upper stage orbital transfer vehicles. Wants to improve system capability by introducing advanced solar upper stage or orbital transfer vehicle propulsion concepts. Has conceptualized, designed and analyzed innovative approaches for SLPREs. Is in the process of developing and fabricating one or more SLPRE prototypes.

OL-AC PL/RKES: Maintains the Air Force Solar Laboratory Facility at Edwards AFB in California, it is a state-of-the-art, solar-powered test facility complete with a vacuum system which is capable of simulating altitude required to conduct controlled tests of solar energy usable hardware. Employs personnel experienced in setting up, troubleshooting, conducting and analyzing tests on solar thermal propulsion hardware. Operates the aforementioned laboratory under various conditions to test a wide range of hardware. Equipment is kept in a high state of readiness, and personnel maintain a high degree of expertise.

DESCRIPTION OF CONCEPT

The solar thermal propulsion system consists of two primary concentrators, one or two thrusters, propellant tank, controls, sun-tracking system, and associated hardware.

³Toni Zlebek, ITT Statistical Programs Group Presentation of Taguchi Methods, 19-26 Feb 1991, based on Dr. Genuchi Taguchi's Design of Experiments.

Sunlight is collected and focused through two apertures (180° apart) from the primary concentrators. Solar energy may be further focused by secondary concentrators positioned between the primary concentrators and the thruster apertures. The thermal energy is then absorbed by a heat exchanger which transfers the heat to the propellant. The propellant expands through the nozzle(s), producing thrust. There is no ignition or combustion of the hydrogen propellant; no oxidizer is used.

Concentrators have two degrees of freedom of movement to allow power reception and thrust simultaneously. The concentrators are required to put the center of mass on the thrust line so that spacecraft can be operated in a solar thermal propulsion mode.⁴ Both mirrors need to track the sun at the same time to get enough energy into the hydrogen gas to expand it out the propulsive nozzle. Only one of the two mirrors need be used to track the laser to get the hydrogen gas to expand and produce thrust. There are other variations that may be considered. Size will be determined by mission requirements for thrust and available laser intensity.

ADVANTAGES

Thrust is proportional to the useful collected solar power. The higher the temperature of the system (up to the thermodynamic limit), the higher the achievable thrust. High Specific Impulse may be achieved; possibly 1000 sec using hydrogen gas (cryogen) as the propellant or about 450 sec using ammonia (storable) as the propellant. Almost any gas can be used as the propellant: hydrogen, ammonia, hydrazine, helium, argon, etc. Only the propellant is carried to orbit.⁵ The energy source is the sun or a ground based laser.

The concentrator need only be as large as the laser spot size. If properly designed, the system could work satisfactorily in either laser or solar thermal propulsion mode. The entrance apertures of the secondary concentrator and the absorber can be much smaller if operated in laser thermal mode. This is because laser light can be focused to a much smaller spot for the same input power. The solar mode would produce lower thrust during intervals when a laser ground station was not in view. When the spacecraft is eclipsed from the sun, the laser power beaming should cause it through at higher thrust, faster.

The Propulsion Directorate will test the solar mode operation on the ground using OL-AC PL/RKES existing solar thermal propulsion facilities and hardware. The la-

⁴Michael R. Holmes and Kristi K. Laug, Dependence of Solar-Thermal Rocket Performance on Concentrator Performance, 1995 ASME/ASME/ISE International Solar Energy Conference Proceedings, Maui HI, 19-24 March 1995, Vol 2, pp. 837-848.

⁵Holmes and Laug

mode of operation on the ground was tested using PL/LIDB existing laser facilities and hardware.⁶

DISADVANTAGES

A cryogenic fuel is not desirable for satellite repositioning missions. A storable propellant must either be carried, made, or accessed in space to make it profitable or even possible. Most times, strictly solar powered maneuvering will be much slower than laser powered maneuvering, but more consistent, especially in the more distant orbits.

EXPERIMENTS

During the summers of 1994 and 1995 the Solar Propulsion Group at Edwards AFB worked on the design, fabrication, and test of our Reticulated Vitreous Carbon Calorimeter (RVCC) as a Volumetric Absorber Solar Engine.⁷ The wafers were deemed fit to test in a harsh laser environment. They survived the testing in the Phillips Laboratory Laser Imaging Group's (PL/LIDB) Chemical Oxygen Iodine Laser (COIL) for the most part. Some wafers did receive a fair amount of damage.⁸ See Figures 3 through 6 below. Figures 3 and 4 are prelased wafers. Figures 5 and 6 are the same wafers after lasing.

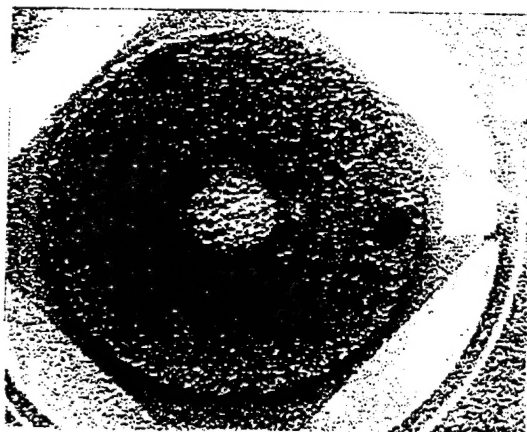


Fig. 3 Prelased Hafnium Carbide Wafer (M-13)

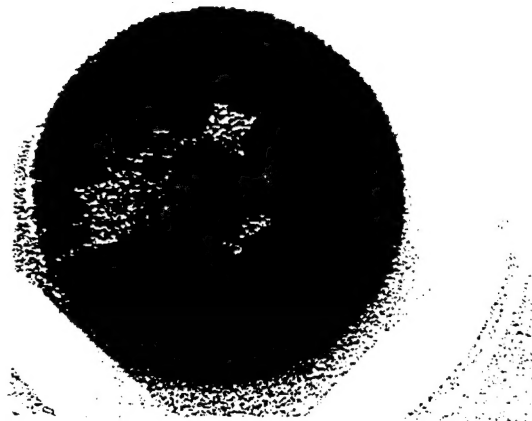


Fig. 4 Prelased Hafnium Carbide Wafer (M-13 Reverse)



Fig. 5 Lased Hafnium Carbide Wafer (M-13)

⁶Laug & Holtzclaw, Volumetric Absorber as Solar Engine Utilizing Laser Thermal Power for Energy Input

⁷Kristi K. Laug and Alan J. Baxter, Evaluation of Hafnium Carbide Wafers for use in a Solar Calorimeter, 13th Symposium on Space Nuclear Power and Propulsion (SNPP), Proceedings of the Space Technology and Applications International Forum (STAIF-96), 8-11 January 1996.

⁸Laug and Holtzclaw, Volumetric Absorber as Solar Engine Utilizing Laser Thermal Power for Energy Input.

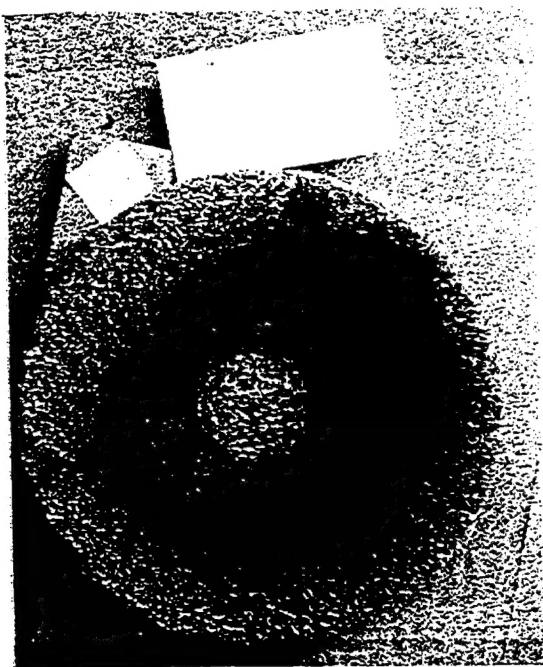


Fig. 6 Lased Hafnium Carbide Wafer
(M-13 Reverse)

Test Hardware and Setup Description

The RVCC cavity is 190.5 mm (7.5 in.) nominal internal diameter. It is approximately 457.2 mm (18 in.) in length. It converges down to 25.4 mm (1 in.) diameter at the outlet. It is not equipped with a nozzle; therefore it is not a thruster. The RVCC is made of a 203.2 mm (8 in.) stainless steel pipe and one end cap nested inside a 254 mm (10 in.) stainless steel pipe and one end cap. At the other end is a 203.2 mm (8 in.) to 254 mm (10 in.) *annular* pipe cap, joining the two pipes. The seams are all welded. Long fins were welded in a helix around the outside of the inner pipe, to direct cooling water flow. See Figure 7. Reticulated vitreous carbon and/or hafnium carbide discs are pushed in through the front behind the window (which is removable) a specified distance. See Figure 8.

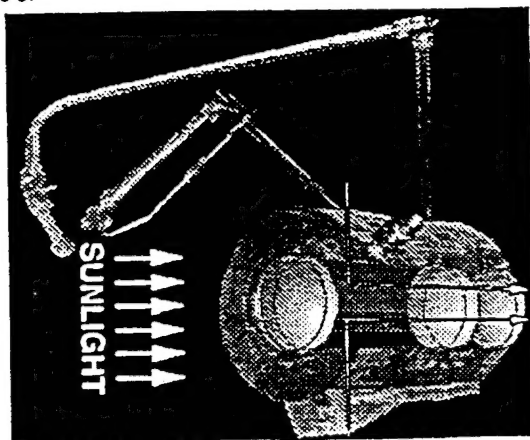


Fig. 7 RVCC Assembly Schematic

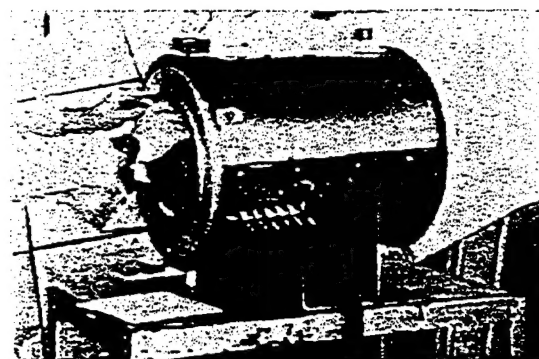


Fig. 8 RVCC Disc Installation

Helium propellant enters the front of the cavity (a cross section) through a tube. It is held inside the cavity behind the quartz window. The propellant exits the opposite end, through a tube to a heat exchanger.

There are 14 sealed thermocouple ports inserted through the double walls of the RVCC, 2 each station, 180 degrees apart, axially. There are 12 Type C (26% tungsten-rhenium) thermocouples inserted into the instrument ports along with one pressure transducer. Seven stations were designated. The stations served as positioning locations for the wafers. Two types of wafers were inserted: carbon (C), and hafnium carbide chemical vapor deposited (HfC) on carbon foam blanks (HfC).

The variables are all related to physical characteristics of the wafers, or influences that affect the solar furnace. They include the following. The wafer porosity ranged from 10 to 100 ppi. The wafer material was either carbon or hafnium carbide. The wafers came in three thicknesses: 12.7 mm (.5 in.), 25.4 mm (1 in.), or 50.8 mm (2 in.). From that, it is possible the position of the wafers in the cavity, the thickness of the front wafer, and the porosity of individual wafers in the stack all had bearing on the output. Other considerations, such as density of the hafnium carbide, shape of the pores, shininess, etc., had to be lumped in as signal and noise factors under thermal conductivity. Propellant pressure through the wafers, wafer color, and thermocouple reading at each station.

The solar facility itself had variables that had to be considered. The first and foremost obvious parameter was the sun quality. It could be a very finely tuned variable. We had set the door height at levels to exactly correspond with a given power rating, but that would increase the need to such a degree it was not practical. Suffice to say the heights (fully and half open for 24.7 kW and 12.3 kW, respectively) are acceptable. The sun quality varies with seasonal variations affecting the Earth. For instance, the shortest days of the year from 8 December to 8 January the sun is not shining through as much atmosphere as it is

the longest days (8 June to 8 July). However, the angle is greater because of the elliptical orbit of the earth and the 23 degree tilt of the axis. On the longest days the sun is at a more direct angle, but it is farther away. Then there are the points in between. Four basic seasons were chosen instead of months to cut down the number of factors.

Then there are several hours each day that work to vary the data. We chose 11:30am and 1:30pm because no matter the season of the year, those two times are always available as test times. 12:30pm could have been used, but again that increased the number of factors without gaining enough in return.

As for the furnace itself, propellant flowrate could have been varied infinitely. We chose three flowrates for the tests. We chose two propellants to use as the fuel (hydrogen and helium). There are many others, but we're set up for using those two.

The concentration ratio varies as the size of the primary concentrator area over the entrance aperture area of the test article (geometric). That changes over the course of the day somewhat because our heliostat is not flat, and the shape is not perfect, but assume it remains close to 8000 : 1 for the tests.

Temperature can be an important factor, controllable or not. Some data will hinge the temperatures of various coolants in the lab. Placement of thermocouples before or after or in the middle of certain stations will affect the reduced overall data.

We run a gaseous nitrogen ejector to drag the fuel molecules out of the altitude chamber. The pressure could be varied infinitely, but we chose 690 kPa to 3447 kPa (100 psi and 500 psi)

Another factor that dictates when we can test is windspeed. If the windspeed climbs to greater than 15 km per hour, the heliostat we use to track the sun bounces and causes the spot focus to move. Tracking parameters could be considered as a variable, but they were rolled into the heliostat diffusivity, intensity, and flux signal factors.

A statistical experimental design method was used to determine the test matrix. It was loosely based on Taguchi's Design of Experiments. The test matrix pitted the wafer porosity against type against power rating and propellant flow rate among other variables. The design mapped out many more parameters and variables than was practical, using Taguchi's methods. See the paragraphs below for more information.

Assumptions

The experimental data must be repeatable. In this case, it will be difficult because of dealing with changing conditions from day to day, even minute to minute. Assume that test conditions can be duplicated on a day during a given season that will be similar to the day the original data was taken.

The population follows normal distribution. Assume this to be true. Each level of a factor has identical variance. The data will be obtained at random within the seasonal constraints put on the testing.

Method

Taguchi Design of Experiments

The Taguchi Design of Experiments method is a statistical analysis method. Supposedly there are a specific number of parameters that are grouped, considered, and varied as part of the experimental design process. The idea is to shorten the number of tests, while increasing the knowledge about each test and its relationship to other tests. This is supposed to cover several items of information per test that will correlate with other sets of data from other tests. If the number of parameters grows, to cover all of the possibilities, the matrix size becomes unwieldy, making it very difficult to determine the statistical analysis of variance (ANOVA) tables.⁹ If the number is lessened, the matrix becomes suspect because there may not be enough information to base a decision.

There are three basic groups of factors that must be brainstormed, shuffled, and apportioned. They are the Quality Characteristics (QCs) or parameters which directly affect the output; Signal Factors; and Noise Factors. Signal Factors are those you have some minimal control over, or can rate in numerical terms or groups that can be dealt with logically. Noise Factors are totally uncontrollable.

The following sections describe the steps were taken and how the design of experiments test matrix was accomplished. First, the subject descriptions were listed, assigned alpha numerics, and placed in a table called the Factor Group Listing. See Table 1 below.

⁹Ziebek, Taguchi Design of Experiments

Table 1 Factor Group Listing

LETTER DESIGNATION	QUALITY CHARACTERISTICS	NOISE FACTOR	SIGNAL FACTOR
A	laboratory door height (half or fully open)		propellant pressure
B			
C	propellant flow rate (1, 3, or 6 grams per sec)		
D	water pore size (nominally 20, 40, 60, or 100 ppi)		
E	thickness of stacked wafers of a given ppi (1/2 in, 2 in, or 3 1/2 in thick)	number wafers stacked (distance within cavity length)	
F	gasous nitrogen ejector pressure (100 or 500 psi)		
G		concentration ratio	
H			
I	time of day (11:30 or 13:30)		
J			
K	material (carbon-C or hafnium carbide-M)		
L			
M		thermal conductivity	
N	season (winter: 30 Nov to 31 Jan, spring: 1 Feb to 15 May, summer: 16 May to 23 Aug, fall: 24 Aug to 28 Nov)		air temperature (ambient)
O			water inlet temperature
P			propellant temperature
Q			heliosat diffusivity
R			width of concentrator intensity distribution on target
S			height of concentrator intensity distribution on target
T			wafer color
U			normal incidence pyrheliometer reading (lux)
V			
W	thermocouple placement (centered on wafer edge or between wafers)	propellant type (helium or hydrogen)	
X			
Y	wafer placement (toward front or rear)	thermocouple reading at each station	
Z			
AA			wafers single or combo to get stacked height
AB	thinnest wafer position (front or rear of stack)		same wafer combo and order or different
AC			from last time particular stack used
AD			wind speed

The best way to determine the factors was to cor brainstorming session. Then levels of values and deg freedom for each one were added. If the list is too lor is, greater than the orthogonal array that can be worke eliminate some. Like variables were combined possible. The degrees of freedom are the number of minus one. Next, the appropriate orthogonal array ascertained for each group of factors in the listing signal, or noise) and the ANOVA tables determined target values. Finally, the significant variables were se The experiments will be performed as random possible.¹⁰ Then find out if there are any matches. point either go back to square one with a better underst of the mechanisms involved so it can be done right th time. If the experimental process is successful, th fodder for a really good paper.

While some of the reasons behind the factors group immediately apparent, some are not. For instance, combinations, or placement of a given wafer in a st wafers may not seem to have much of an impact on th if all the wafers are the same porosity, or the same thic However, when flowing a gas over the wafers that are by convection, radiation, and conduction, there m eddies and currents introduced that could affect the Imagine how the listed interactions may occur. The c cause one wafer in the middle to cool down in one are still allowing the wafers around it to become heated. not occur if a particular wafer is moved to another p As seen in Table 2, the QCs are very well defined in te levels, degrees of freedom, and specific values.

¹⁰Ibid.

Table 2 QC Leveling and Degrees of Freedom Determination

ALPHA	QC's ONLY DESCRIPTION	LEVEL DESCRIPTION	LEVEL ALPHA	NUMBER OF LEVELS	DEGREES OF FREEDOM
A	door height	1/2 (full open), 1 (fully open)	A1A2	2	1
B	propellant flow	1, 3, 8 grams/sec	G1,G2,G3	3	2
C	door vs. propellant flow interaction suspected	20, 40, 60, 100 psi	D1,D2,D3,D04	4	3
D	water pore size	1/2 in, 2 in, 3 1/2 in	F1,F2,F3	3	2
E	stacked height	500 psi, 100 psi	G1,G2	2	1
F	selector pressure	11-30, 13-30 test time	H1,H2	2	1
G	line of day	C or M	K1,K2	2	1
K	material		AC1,AC2,AC3	3	2
A x C	door vs. propellant flow interaction suspected		CD1,CD2,CD3,CD4,CD5,CD6,CD7	7	6
A x D	propellant flow vs. water pore size interaction suspected		CF1,CF2,CF3,CF4,CF5	5	4
C x D	propellant flow vs. stacked water height interaction suspected		G1,G2,G3	3	2
C x F	propellant flow vs. line of day interaction suspected		NI,N2,N3,N4	4	3
C x I	season	W, S, S, F	W1,W2	2	1
N	in-miscible placements	between walers or centered on edge	Y1,Y2	2	1
W	position of walers in cavity	toward front or rear	AB1,AB2	2	1
Y	skinny water position	toward front or rear			
AB				48	31

This paper is not going to describe everything done by Taguchi's methods. That is well-defined in several volumes and treatises. However, based on the above information it can be seen how the following tables were generated. Build an ANOVA Table as seen in Table 3.

Do the same leveling and dof determination for the signal factors and noise factors using Table 2 as a guide. See the following tables (4 and 5).

Table 3 QC ANOVA Table for No Target Value Specified

[illegible]

Table 4 Signal Factors Levelling and Degrees of Freedom Determination

ALPHA	SIGNAL FACTORS DESCRIPTION	LEVEL DESCRIPTION minus 0 positive	LEVEL ALPHA	NUMBER OF LEVELS	DEGREES OF FREEDOM
B	propellant pressure	low normal	B1 B2 B3	3	2
O	ambient air temperature	30 70	O1 O2 O3	3	2
P	water inlet temperature	40 70	P1 P2 P3	3	2
Q	propellant temperature	<-450 -450	Q1 Q2 Q3	3	2
R	heliosat diffusivity	<100% 100%	R1 R2 R3	3	2
S	width of concentrator intensity distribution on target	narrow normal	S1 S2 S3	3	2
T	height of concentrator intensity distribution on target	high normal	T1 T2 T3	3	2
U	water color	black gray	U1 U2 U3	3	2
V	normal incidence pyrheliometer reading	<25 mV 25 mV	V1 V2 V3	3	2
AA	waters single or combo to get stacked height	single	AA1 AA2	2	1
AC	same water combo and order or different from last time particular stack used	diff	AC1 AC2	2	1
AD	wind speed	>30 mph 30 mph	AD1 AD2	3	2
	TOTAL			34	22

$L_{27}(3)^{13}$

Build the Signal Factors and Noise Factors ANOVA just like for the QC ANOVA Table 3 above. Don't after the ANOVA Tables are filled in you must pc small Ss within the column together.¹¹ They hav impact and if done correctly, it will save time later performing the calculations on the data reductions.

Table 5 Noise Factors Levelling and Degrees of Freee Determination

ALPHA	NOISE FACTORS DESCRIPTION	LEVEL DESCRIPTION minus 0 positive	LEVEL ALPHA	NUMBER OF LEVELS	DEGREES OF FREEDOM
E	number stacked waters	low normal	E1 E2 E3	3	2
H	concentration ratio	low normal	H1 H2 H3	3	2
M	thermal conductivity	low normal	M1 M2 M3	3	2
X	propellant type (helium or hydrogen)	gt12	X1 X2	3	2
Z	thermocouple reading each station	< equal	Z1 Z2 Z3	3	2
	TOTAL			15	9

$L_{12}(2)^{11}$

¹¹ Ibid.



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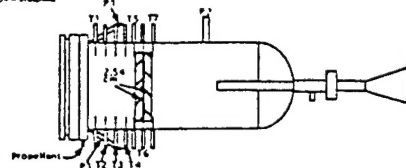
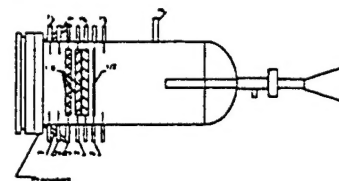
	Y	Y1	Y2	Y3
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¹²Ibid.

$\frac{r}{n}, r$	\bar{y}	Y_4	$5 \times \frac{1}{2} (n-r)^2$	$\sigma^2 \mu^{r-1} \sigma^2 \mu^{r-1} \dots \frac{1}{2} \mu^{r-1} \sigma^2 \mu^{r-1} \dots \frac{1}{2} \mu^{r-1} \sigma^2$	$v = (1-\sigma^2 - n) d f, \dots \sum_{i=1}^n (v_i^2 - \bar{v})^2) / (n-1)$	$\dots \sqrt{5/72}$
y_1	$y_1/1$	y_1^2	$y_1^2 - \Sigma (y_i \cdot y_i)$	$y_1^2 - \Sigma (y_i \cdot y_i)$	$n(y_1^2 - y_1)^2 / n$	\sqrt{n}
y_2	$(y_1 + y_2) / 2$	y_2^2	$y_1^2 + y_2^2 - \Sigma (y_i \cdot y_i)$	$y_1^2 + y_2^2 - \Sigma (y_i \cdot y_i)$	$n(y_1^2 - y_1)^2 / n$	\sqrt{n}
y_3	$(y_1 + y_2 + y_3) / 3$	y_3^2	$y_1^2 + y_2^2 + y_3^2 - \Sigma (y_i \cdot y_i)$	$y_1^2 + y_2^2 + y_3^2 - \Sigma (y_i \cdot y_i)$	$n(y_1^2 - y_1)^2 / n$	\sqrt{n}
y_4	$(y_1 + y_2 + y_3 + y_4) / 4$	y_4^2	$y_1^2 + y_2^2 + y_3^2 + y_4^2 - \Sigma (y_i \cdot y_i)$	$y_1^2 + y_2^2 + y_3^2 + y_4^2 - \Sigma (y_i \cdot y_i)$	$n(y_1^2 - y_1)^2 / n$	\sqrt{n}
y_5	$(y_1 + y_2 + y_3 + y_4 + y_5) / 5$	y_5^2	$y_1^2 + y_2^2 + y_3^2 + y_4^2 + y_5^2 - \Sigma (y_i \cdot y_i)$	$y_1^2 + y_2^2 + y_3^2 + y_4^2 + y_5^2 - \Sigma (y_i \cdot y_i)$	$n(y_1^2 - y_1)^2 / n$	\sqrt{n}
y_6	$(y_1 + y_2 + y_3 + y_4 + y_5 + y_6) / 6$	y_6^2	$y_1^2 + y_2^2 + y_3^2 + y_4^2 + y_5^2 + y_6^2 - \Sigma (y_i \cdot y_i)$	$y_1^2 + y_2^2 + y_3^2 + y_4^2 + y_5^2 + y_6^2 - \Sigma (y_i \cdot y_i)$	$n(y_1^2 - y_1)^2 / n$	\sqrt{n}
y_7	$(y_1 + y_2 + y_3 + y_4 + y_5 + y_6 + y_7) / 7$	y_7^2	$y_1^2 + y_2^2 + y_3^2 + y_4^2 + y_5^2 + y_6^2 + y_7^2 - \Sigma (y_i \cdot y_i)$	$y_1^2 + y_2^2 + y_3^2 + y_4^2 + y_5^2 + y_6^2 + y_7^2 - \Sigma (y_i \cdot y_i)$	$n(y_1^2 - y_1)^2 / n$	\sqrt{n}
y_8	$(y_1 + y_2 + y_3 + y_4 + y_5 + y_6 + y_7 + y_8) / 8$	y_8^2	$y_1^2 + y_2^2 + y_3^2 + y_4^2 + y_5^2 + y_6^2 + y_7^2 + y_8^2 - \Sigma (y_i \cdot y_i)$	$y_1^2 + y_2^2 + y_3^2 + y_4^2 + y_5^2 + y_6^2 + y_7^2 + y_8^2 - \Sigma (y_i \cdot y_i)$	$n(y_1^2 - y_1)^2 / n$	\sqrt{n}
y_9	$(y_1 + y_2 + y_3 + y_4 + y_5 + y_6 + y_7 + y_8 + y_9) / 9$	y_9^2	$y_1^2 + y_2^2 + y_3^2 + y_4^2 + y_5^2 + y_6^2 + y_7^2 + y_8^2 + y_9^2 - \Sigma (y_i \cdot y_i)$	$y_1^2 + y_2^2 + y_3^2 + y_4^2 + y_5^2 + y_6^2 + y_7^2 + y_8^2 + y_9^2 - \Sigma (y_i \cdot y_i)$	$n(y_1^2 - y_1)^2 / n$	\sqrt{n}
y_m	$(y_1 + y_2 + y_3 + y_4 + y_5 + y_6 + y_7 + y_8 + y_9 + y_m) / m$	y_m^2	$y_1^2 + y_2^2 + y_3^2 + y_4^2 + y_5^2 + y_6^2 + y_7^2 + y_8^2 + y_9^2 + y_m^2 - \Sigma (y_i \cdot y_i)$	$y_1^2 + y_2^2 + y_3^2 + y_4^2 + y_5^2 + y_6^2 + y_7^2 + y_8^2 + y_9^2 + y_m^2 - \Sigma (y_i \cdot y_i)$	$n(y_1^2 - y_1)^2 / n$	\sqrt{n}
$\frac{\Sigma y_i}{n}$	$\frac{\Sigma y_i}{n}$		Σy_i	Σy_i	Σy_i	Σy_i

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RESULTS/CONCLUSIONS

There aren't any results yet because no tests have been performed to date. Testing will take over a year to complete; tests are planned over the course of four seasons.

By using the Taguchi DOE, we expect to cut down the number of experiments from greater than 140 down to less than 40. This will save time, energy, and money in terms of tests, propellant, manhours, and computer time. At the same time, it should give us more useful and correlatable data.